MICROCOPY RESOLUTION TEST CHART

NATIONAL BUREAU OF STANDARDS-1963-A

STUDIES IN STATISTICAL SIGNAL PROCESSING

Annual Scientific Report

Submitted by:

Thomas Kailath
Information Systems Laboratory
Stanford University
Stanford, CA 94305

DTIC
SELECTED
NOV 1 1984
D

August 28, 1984

84 10 050

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION	1b RESTRICTIVE MARKINGS
UNCLASSIFIED	

2a SECURITY CLASSIFICATION AUTHORITY	3 DISTRIBUTION AVAILABILITY OF REPORT
2b DECLASSIFICATION DOWNGRADING SCHEDULE	Approved for public release; distribution unlimited.

4 PERFORMING ORGANIZATION REPORT NUMBER(S)	5 MONITORING ORGANIZATION REPORT NUMBER(S)
	AFOSR·TR· 84-0868

6a NAME OF PERFORMING ORGANIZATION	6b OFFICE SYMBOL (If applicable)	7a NAME OF MONITORING ORGANIZATION
Stanford University		Air Force Office of Scientific Research

6c ADDRESS (City, State, and ZIP Code)	7b ADDRESS (City, State, and ZIP Code)
Department of Electrical Engineering Stanford CA 94305	Directorate of Mathematical & Information Sciences, AFOSR, Bolling AFB DC 20332

8a NAME OF FUNDING/SPONSORING ORGANIZATION	8b OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
AFOSR	NM	AFOSR-83-0228

8c ADDRESS (City, State, and ZIP Code)	10 SOURCE OF FUNDING NUMBERS			
Bolling AFB DC 20332	PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.
	61102F	2304	A6	

11 TITLE (Include Security Classification)
STUDIES IN STATISTICAL SIGNAL PROCESSING

12 PERSONAL AUTHOR(S)
Thomas Kailath

13a TYPE OF REPORT	13b TIME COVERED	14 DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Interim	FROM 1/7/83 TO 30/6/84	28 AUG 84	7

16 SUPPLEMENTARY NOTATION

COSATI CODES			18 SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	Stochastic processes; second-order processes; least-squares estimation; lattice filters; adaptive filters; adaptive beamforming; fast algorithms.

19 ABSTRACT (Continue on reverse if necessary and identify by block number)

Several new results in the modeling, analysis and prediction of nonstationary second order processes have been developed. They include (1) the derivation of constant-parameter lattice filters for general nonstationary processes; (2) the development of fast algorithms for adaptive filtering with fixed-order transversal filters, including modifications necessary to ensure stability and convergence with finite precision computations; (3) the invention of a new adaptive beam-forming array for separating coherent (completely correlated) signals and interference. Two Ph.D. theses have been completed during this period, H. Lev-Ari, "Nonstationary Lattice-Filter Modeling," December 1983 and J.M. Cioffi, "Fast Transversal Filters for Communications Applications," March 1984.

20 DISTRIBUTION/AVAILABILITY OF ABSTRACT	21 ABSTRACT SECURITY CLASSIFICATION
☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	UNCLASSIFIED

22a NAME OF RESPONSIBLE INDIVIDUAL	22b TELEPHONE (Include Area Code)	22c OFFICE SYMBOL
MAJ Brian W. Woodruff	(202) 767-5027	NM

DD FORM 1473, 84 MAR   83 APR edition may be used until exhausted
All other editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

II. Objectives of the Research

To develop efficient algorithms for a variety of nonstationary signal process-
ing problems by understanding and exploiting special structures--deterministic
and stochastic--in the problems.

II. Status of Research

We describe below two major areas of research activity in the period July 1,
1983 through June 30, 1984 and indicate the directions in which further work is
being pursued. A list of publications, published journal papers, accepted papers,
published conference papers and conference presentations and seminars is pro-
vided and should also give an indication of the research activity.

A. Fundamental Theory of Second-Order Nonstationary Processes

The major accomplishments were the completion of the thesis by H. Lev-Ari,
entitled "Nonstationary Lattice-Filter Modeling" and the thesis of J. Cioffi enti-
tled "Fast Transversal Filters for Communications Applications".

As stated in the introduction to Lev-Ari's thesis, for more than four decades,
the notion of stationarity has dominated the theory and practice of numerous
scientific disciplines, including information theory, communications, signal pro-
cessing, seismic exploration, and time-series analysis. Its successful exploitation in
a variety of particular problems created the impression that most physical
phenomena could be approximated with reasonable accuracy by stationary
models. This "stationarity illusion" attracted most of the research effort to the
study of stationary models, creating a severe lack of analytical tools for modeling
and analysis of nonstationary processes. The unavoidable consequence was a
widespread belief that the study of nonstationarity could not be carried out
without sacrificing the simplicity and intuitive appeal of stationary models.

The results of the research clearly reported in the above dissertations
demonstrate the possibility of constructing simple models for nonstationary
phenomena. The research spans a wide range of topics, beginning with the
derivation of a canonical parametrization of nonstationary covariances, proceed-
ing through covariance extension and interpolation problems, and culminating in
the construction of lattice-form modeling and whitening filters. Several results
previously widely believed to only hold for stationary processes are extended in
nontrivial ways to a general class of nonstationary processes. The true
significance of many special stationary process results is uncovered. Applications
to several important communications problems are developed. Three long papers
on parts of this work have already appeared (*IEEE Trans. Inform. Thy.*, pp. 2-
16, January 1984 and pp. 222-236, March 1984, and *IEEE Trans. ASSP*, pp.

304-337, April 1984) and several more are currently in preparation. To speed this process, Dr. Lev-Ari will be a part time Research Associate from October 1984.

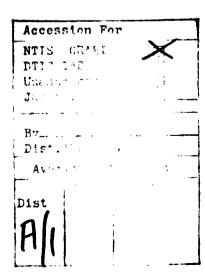## B. Antenna Arrays for Adaptive Beam Forming

The other major research result has been the discovery of a new antenna beam-forming scheme for adaptively rejecting interfering signals that may be completely coherent with the desired signal. Coherent interference is one that has a *fixed phase relationship* with the desired signal, as can arise in multipath and "smart jamming" environments. We have developed a new scheme for combating such interference in the case of planewave (far-field) interference and a stationary uniformly spaced linear array. A patent application has been filed by Stanford University for this scheme. (An invention disclosure was previously filed with AFOSR). These results were presented at the Asilomar Conference and at the ASSP Spectral Estimation Workshop, Tampa, FL, in November 1983. A paper on this has been accepted by the *IEEE Transactions on Acoustics, Speech and Signal Processing.*

Several aspects of the closely related direction finding problem are being developed by Mati Wax, whose Ph.D. dissertation should be completed by December 1984. Several papers based on his earlier research appear in the publications list. Current effort is being devoted to comparing the presently known eigenstructure (MUSIC) algorithms with the optimal Maximum Likelihood solution.

C. Other Topics

The publications list contains papers based on prior research as well as some conference papers describing work in progress.

III. Publications

Published Journal (or book) Papers

T. Kailath and M. Wax, "A Note on the Complementary Model of Weinert and Desai," *IEEE Trans. Autom. Contr.*, Vol. AC-29, no.6, pp. 551-552, June 1984.

H. Lev-Ari, J. Cioffi and T. Kailath, "Least-Squares Adaptive-Lattice and Transversal Filters: A Unified Geometric Theory," *IEEE Trans. on Inform. Thy.*, (special issue), Vol. IT-30, pp. 222-236, March 1984.

J. M. Cioffi and T. Kailath, "Fast, Recursive-Least-Squares Transversal Filters for Adaptive Filtering," *IEEE Trans. ASSP*, Vol. ASSP-32, no. 2, pp. 304-337, April 1984.

M. Wax and T. Kailath, "Direct Approach to the Two-Filter Smoothing Formulas," *Inter'l. J. Control*, Vol. 39, no. 3, pp. 517-522, 1984.

H. Lev-Ari and T. Kailath, "Lattice Filter Parametrization and Modeling of Nonstationary Processes," *IEEE Trans. Inform. Thy.*, Vol. IT-30, no. 1, pp. 2-16, January 1984.

B. Egardt, T. Kailath and V. U. Reddy, "High-Resolution Spectral Analysis using Multi-Step Adaptive Prediction," *Circuits, Systems and Signal Processing*, Vol. 2, no. 4, pp. 422-443, 1983.

M. Wax, "Position-Location from Sensors with Position Uncertainty," *IEEE Trans. AES*, Vol. 19, no. 5, pp. 658-602, September 1983.

M. Wax and T. Kailath, "Optimum Localization of Multiple Sources in Passive Arrays," *IEEE Trans. ASSP*, Vol. ASSP-31, no. 5, pp. 1210-1218, October 1983.

M. Wax and T. Kailath, "Efficient Inversion of Doubly Block Toeplitz Matrix," *IEEE Trans. ASSP*, Vol. ASSP-31, no. 5, pp. 1218-1221, October 1983.

T. Kailath, L. Ljung and M. Morf, "Recursive Input-Output and State-Space Solutions for Continuous-Time Linear Estimation Problems," *IEEE Trans. Autom. Contr.*, Vol. AC-28, no. 9, pp. 897-906, September 1983.

E. I. Verriest and T. Kailath, "On Generalized Balanced Realizations," *IEEE Trans. on Autom. Contr.*, Vol. AC--28, no. 8, pp. 833-844, August 1983.

Published Conference Papers

T. Kailath, A. Bruckstein and D. Morgan, "Fast Matrix Factorization via Discrete Transmission Lines," American Math. Soc. Meeting, *Linear Algebra and Its Role in Systems Theory*, July, 1984. Abstract

J. M. Cioffi and T. Kailath, "An Efficient, Recursive-Least Squares, Fractionally Spaced Equalizer using Intersymbol Interpolation," *ICC'84*, Amsterdam, Holland, May 14-17, 1984.

T. J. Shan and T. Kailath, "New Adaptive Processor for Coherent Signals and Interference" *ICASSP*, pp. 33.5.1-33.5.4, San Diego, CA, March 1984.

M. Wax and T. Kailath, "Determining the Number of Signals by Akaike's Information Criterion," *ICASSP*, pp. 6.3.1-6.3.4, San Diego, CA, March 1984.

M. Wax and T. Kailath, "A New Approach to Decentralized Array Processing," *ICASSP*, pp. 40.7.1-40.7.4, San Diego, CA, March 1984.

S. K. Rao and T. Kailath, "Pipelined Orthogonal Digital Lattice Filters," *ICASSP*, pp. 11.10.1-11.10.4, San Diego, CA, March 1984.

H. Lev-Ari and T. Kailath, "Spectral Analysis of Nonstationary Processes," *IEEE Inter'l. Symp. on Inform. Thy.*, St. Jovite, Quebec, Canada, Sept. 1983. Abstract.

T. J. Shan, M. Wax and T. Kailath, "Spatial Smoothing Approach for Location Estimation of Coherent Sources," *17th Asilomar Conference on Circuits, Systems and Computers*, Monterey, CA, Oct. 1983.

T. J. Shan, and T. Kailath, "A New Adaptive Antenna System for Coherent Signals and Interference," *17th Asilomar Conference on Circuits, Systems and Computers*, Monterey, CA, Oct. 1983.

T. Kailath, "Estimation and Control in the VLSI Era," *The 22nd IEEE Conf. on Decision & Contr.*, San Antonio, TX, Dec. 1983.

A. M. Bruckstein and T. Kailath, "Modeling Rate-Modulated Selfexciting Point Processes," *Proc. of Systems, Man and Cybernetics Conference*, pp. 431-433, Bombay & New Delhi, India, Dec. 31, 1983.

M. Wax, T. Kailath and R. O. Schmidt, "Retrieving the Poles from the Natural Response by Eigenstructure Method," *The 22nd IEEE Conf. on Decision and Control*, San Antonio, TX, December 14-16, 1983.

M. Wax and T. Kailath, "Determining the Number of Signals by Information Theoretic Criteria," *ASSP Spectrum Estimation Workshop II*, Tampa, FL, November 10-11, 1983.

T. J. Shan and T. Kailath, "Adaptive Beamforming for Coherent Signals and Interference," *ASSP Spectrum Estimation Workshop II*, Tampa, FL, November 10-11, 1983.

M. Wax, T-J. Shan and T. Kailath, "Covariance Eigenstructure Approach to

Detection and Estimation by Passive Arrays," Pt. I: Direction-of-Arrival and Frequency Estimation of Multiple Narrowband Sources," *IEEE International Symp. on Inform Thy.* Canada, September 1983.

M. Wax, T-J. Shan and T. Kailath, "Covariance Eigenstructure Approach to Detection and Estimation by Passive Arrays," Pt. II: Source Location and Spectral Density Estimation of Wideband Sources," *IEEE International Symp. on Inform. Thy.*, Canada, September 1983.

Accepted Papers

T. J. Shan and T. Kailath, "Adaptive Beamforming for Coherent Signals and Interference," to appear *IEEE ASSP*, June 1983.

T. J. Shan, M. Wax and T. Kailath, "Spatial Smoothing for Direction-of-Arrival Estimation of Coherent Sources," accepted *IEEE Trans. ASSP.*

M. Wax and T. Kailath, "Detection of Signals by Information Theoretic Criteria," accepted *IEEE Trans. on ASSP.*

M. Wax, T-J. Shan and T. Kailath, "Spatio-Temporal Spectral Analysis by Eigenstructure Methods," accepted *IEEE Trans. ASSP.*

A. M. Bruckstein, B. C. Lévy and T. Kailath, "Differential Methods in Inverse Scattering," accepted *SIAM J. Appl. Math.*

S. R. Rao and T. Kailath, "Orthogonal Digital Filters for VLSI Implementations," *IEEE Trans. Circuits & Systems*, to appear November 1984.

J. M. Cioffi and T. Kailath, "An Efficient, Exact-Least-Squares, Fractionally Spaced Equalizer using Intersymbol Interpolation," accepted *IEEE J. on Selected Areas in Communications*, Special Issue on Data Transmission (Voiceband).

T. Kailath, "Signal Processing in the VLSI Era," to appear in *Modern Signal Processing and VLSI*, ed. by S. Y. Kung, H. Whitehouse and T. Kailath, Prentice-Hall, to appear 1985.

Papers Under Review

S. K. Rao and T. Kailath, "VLSI Arrays for Digital Signal Processing, Pt. I. A Model Identification Approach to Digital Filter Realizations," *IEEE Trans. Circuits and Systems.*

M. Wax and T. Kailath, "Decentralized Processing in Passive Arrays," *IEEE Trans. ASSP.*

A. M. Bruckstein, T. J. Shan and T. Kailath, "The Resolution of Overlapping

Echoes," *IEEE Trans. ASSP.*

J. M. Cioffi and T. Kailath, "An Efficient, High-Performance-Least-Squares, Data-Driven Echo Canceller for Full-Duplex Data Transmission," to be submitted.

J. M. Cioffi and T. Kailath, "Windowing Methods and Their Efficient Transversal-Filter Implementation for the RLS Adaptive-Filtering Criterion," *IEEE Trans. ASSP.*

S. K. Rao and T. Kailath, "VLSI and the Digital Filtering Problem," *Proc. IEEE.*

IV. Professional Personnel

Thomas Kailath, 10% academic, 60% summer

M. Wax

T. J. Shan

A. Bruckstein

H. Lev-Ari (Ph.D. Dissertation 12/83, entitled *Nonstationary Lattice-Filter Modeling*, see attached)

J. M. Cioffi (Ph.D. Dissertation 3/84, entitled *Fast Transversal Filters for Communications Applications*, see attached)

V. Seminars and Lectures

A list of seminars and special lectures is also attached. Particularly noteworthy perhaps are a keynote Plenary Lecture at the Control Systems Society Decision and Control Conference, San Antonio, TX, December 1983. Also 2 out of 12 long papers at the IEEE International Symposium on Information Theory were presented by our group. The Principal Investigator was one of 8 US participants selected for at an US-Japan Bilateral Workshop on Time Series Analysis, Tokyo, Japan, May 1984.

Seminars

Bell Telephone Laboratories, Murray Hill, N.J., August 2-3, 1984.
Indian Institute of Science, Bangalore, India, August 5-18, 1984.
Bell Telephone Laboratories, Holmdel, N.J., October 2-3, 1983.
Stanford University, Department of Mathematics, Stanford, CA, February 17, 1984.
University of Miami, FL, February 23, 1984.

Technion University, Haifa, Israel, April 1984.
Beer-Sheeva University, Beer-Sheeva, Israel, April 5, 1984.
The Weizmann Institute of Science, Rehovot, Israel, April 1984, May 1984.
Tel-Aviv University, Tel-Aviv, Israel, May 1984.

Conferences

22nd Conference on Decision & Control, Keynote Speaker, San Antonio, TX, December 14-16, 1983.

1983 IEEE International Conference on Systems, Man and Cybernetics, Bombay and New Delhi, India, December 30, 1983 - January 7, 1984.

IEEE Conference on Acoustics, Speech and Signal Processing, San Diego, CA, March 19-21, 1984.

9th Annual International Conference on Operator Theory, Bucharest, Romania, June 6-16, 1984.

END

FILMED

11-84

DTIC